

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 2004	3. REPORT TYPE AND DATES COVERED Special Report	
4. TITLE AND SUBTITLE Cockpit Seat and Pilot Helmet Vibration During Flight Operations on Aircraft Carriers			5. FUNDING NUMBERS PE - 62202F PR - 7184 TA - 718402 WU - 71840209	
6. AUTHOR(S) Suzanne D. Smith				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Human Effectiveness Directorate Biosciences and Bioprotection Division Biomechanics Branch Air Force Materiel Command Wright-Patterson AFB OH 45433-7901			8. PERFORMING ORGANIZATION AFRL-HE-WP-TR-2004-0025	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) JSF Program Office 1213 Jefferson Davis Highway Suite 600 Arlington VA 22202			10. SPONSORING/MONITORING	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The objective of this study was to characterize cockpit seat and pilot helmet vibration in a jet aircraft during aircraft carrier flight operations. The Remote Vibration Environment Recorder (REVER) was used to measure triaxial accelerations at the seat base, seat pan, seat back, and helmet in the F/A-18C (Hornet) aircraft during the catapult launch, touch-and-go, and arrested landing. Helmet pitch acceleration and displacement were estimated from the helmet translational acceleration data. Of particular interest was the substantial low frequency seat and helmet vibration observed during the catapult launch. During the stroke period, seat and helmet vertical (Z) accelerations reached 6 g and 8 g peak-to-peak, respectively, and occurred in the frequency range of 3 to 3.5 Hz. The associated helmet pitch reached peak-to-peak displacements ranging between 9 and 18 degrees. The large helmet rotations may be associated with helmet slippage that can cause partial or complete loss of the projected image on a helmet-mounted display (HMD) (vignetting). This is highly undesirable when using the HMD as the primary flight reference (PFR). The aircraft operational vibration can be regenerated in the laboratory for investigating this specific concern. The goal is to develop helmet-mounted equipment design guidelines that consider hostile vibratory environments.				
14. SUBJECT TERMS human vibration, helmet-mounted systems, head vibration, transmissibility			15. NUMBER OF PAGES 8	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

20040331 026

RESEARCH ARTICLE

Cockpit Seat and Pilot Helmet Vibration During Flight Operations on Aircraft Carriers

DISTRIBUTION STATEMENT A

SUZANNE D. SMITH Approved for Public Release
Distribution Unlimited

SMITH SD. Cockpit seat and pilot helmet vibration during flight operations on aircraft carriers. *Aviat Space Environ Med* 2004; 75: 247-54.

Introduction: Human vibration exposure data relative to military tactical and strategic aircraft operations are required for assessing the potential health risks and performance consequences when using helmet-mounted equipment. The objective of this study was to characterize cockpit seat and pilot helmet vibration in a jet aircraft during aircraft carrier flight operations. **Methods:** The Remote Vibration Environment Recorder (REVER) was used to measure triaxial accelerations at the seat base, seat pan, seat back, and helmet in the F/A-18C (Hornet) jet aircraft. Data were collected during flight operations on 2 aircraft carriers for a total of 11 catapult launches (CATs), 9 touch-and-goes (TGs), and 4 arrested landings (TRAPs). Helmet pitch acceleration and displacement were estimated from the helmet translational acceleration data. **Results:** Of particular interest was the substantial low frequency seat and helmet vibration observed during the catapult launch. During the stroke period, seat and helmet vertical (Z) accelerations reached 6 and 8 g peak-to-peak, respectively, and occurred in the frequency range of 3-3.5 Hz. The associated helmet pitch reached peak-to-peak displacements ranging between 9° and 18°. **Discussion:** The large helmet rotations may be associated with helmet slippage that can cause partial or complete loss of the projected image on a helmet-mounted display (HMD) (vignetting). This is highly undesirable when using the HMD as the primary flight reference. The aircraft operational vibration can be regenerated in the laboratory for investigating this specific concern. The goal is to develop helmet-mounted equipment design guidelines that consider hostile vibratory environments.

Keywords: whole-body vibration, helmet-mounted systems, head vibration, transmissibility.

UNTIL RECENTLY, biodynamic data on the transmission of aircraft vibration to the occupants of military fighter aircraft were nonexistent. Any information pertaining to human exposure was extrapolated from structural data available on the vehicle. In general, under good weather conditions and level flight, little vibration of any consequence to human health, safety, or performance is expected in these aircraft. However, undesirable effects may occur under less than ideal weather conditions, during certain tactical maneuvers and special operations, and with the use of head-mounted devices. It is known that head motion can be increased above the vibration level generated at the seat for exposures below 10 Hz due to human body sensitivity in this region (6,7). In addition, helmet weight, center-of-gravity, and head/helmet orientation have all been shown to affect head/helmet motions and may contribute to performance degradation, discomfort, and possibly health effects (1,2,4,8,9). One example of the impact such motions can have on human effectiveness

and the performance of helmet-mounted systems is the low frequency buffeting (7-8.5 Hz) characteristic of aerial combat maneuvers in the F-15 fighter aircraft (10). This buffeting was associated with involuntary head motion that led to a slower than desired target lock-on time of a helmet-mounted targeting and display system.

It is also known that compensatory eye movement becomes ineffective in stabilizing images moving with the head at low frequencies (< 20 Hz), causing visual blurring when using a helmet-mounted display (HMD) (5). During low frequency head rotation, the vestibulo-ocular reflex (VOR) acts to stabilize the line-of-sight between the eye and a viewed object by producing eye rotations in the opposite direction. This compensatory eye movement has been shown to be effective to oscillatory motion as high as 20 Hz (12). Below about 1-2 Hz, pursuit eye movements can suppress the VOR (3). With an HMD, the image moves with the head and compromises the effects of both the VOR and compensatory eye movement, causing visual blurring. In addition, it is speculated that any helmet slippage that may occur during whole-body vibration could exacerbate the visual blurring and even lead to partial or total loss of the projected image (vignetting). Recently, helmet slippage was estimated during laboratory exposures to F-15 buffeting and a flat acceleration spectrum (11). Off-axis head orientations expected to occur during aerial combat maneuvers were shown to significantly increase both the head motion and helmet slippage during both types of exposure.

The Joint Strike Fighter (JSF) program has supported the development of the Remote Vibration Environment Recorder (REVER) and the collection of human vibration data during military flight operations. This study directs attention to the vibration environment occurring in high performance JSF legacy aircraft during aircraft-

From the Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB, OH.

This manuscript was received for review in May 2003. It was revised in September and October 2003. It was accepted for publication in October 2003.

Address reprint requests to: Suzanne D. Smith, Ph.D., AFRL/HEPA, 2800 Q Street, Wright Patterson AFB, OH 45433-7947; suzanne.smith@wpafb.af.mil.

Reprint & Copyright © by Aerospace Medical Association, Alexandria, VA.

carrier flight operations. These operations include the catapult launch (CAT), touch-and-go (TG), and arrested landing (TRAP). Given the restrictive space available on an aircraft carrier for aircraft flight operations, special procedures are used for launch (take-off) and recovery (landing). In addition to the aircraft engines, steam-powered catapults provide thrust to the aircraft during launch (CAT). A launch bar located at the nose landing gear of the aircraft is attached to a catapult shuttle. Once the catapult reaches a predetermined pressure, the shuttle is released in its track and the aircraft travels down the deck. At the end of the stroke period, the shuttle strikes a water break and the aircraft is released, becoming airborne moments later. During a TRAP, a tail hook drops from the rear of the aircraft and snags one of four arresting wires or cables located across the deck. The wires are connected to hydraulic rams located beneath the deck that slow the aircraft to a stop. During a TG, the aircraft contacts the deck for a brief period and takes off again, without snagging a wire.

The objective of the study was to measure and characterize jet aircraft cockpit seat and pilot helmet vibration during the CAT, TG, and TRAP. Data were collected during F/A-18C (Hornet) flight operations aboard two aircraft carriers (Carrier A and Carrier B). REVER was used to collect triaxial acceleration data at the seat and helmet. The goal was to estimate the seat and helmet motions that may be expected in the JSF aircraft during carrier flight operations. These data, along with recent laboratory studies, are being used to identify potential health risks and performance consequences associated with vibration exposure, with the focus on integrating helmet-mounted systems into military tactical and strategic aircraft.

METHODS

This study was exempted from review by an Institutional Review Board since the participants were test pilots performing their normal carrier deck flight duties. This study was conducted as part of an approved Naval Air Systems Command test plan that included an equipment flight clearance.

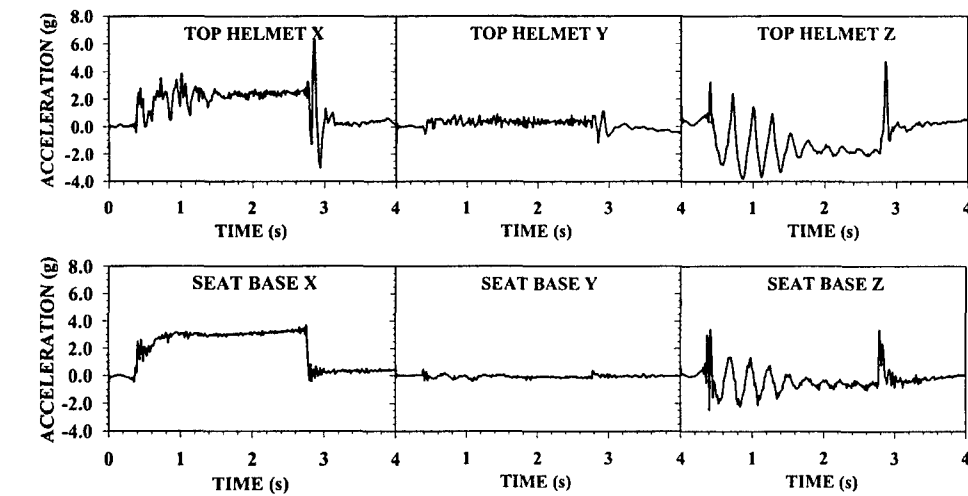
The REVER data acquisition unit (DAU) (EME Corporation, Annapolis, MD) used to collect the seat/helmet acceleration data is a battery-operated system weighing approximately 1.4–1.6 kg and is carried on the inside left pocket of the pilot's survival vest. Triaxial accelerometer packs were attached to the seat and helmet for measuring accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions. The packs were comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin® cylinder. Each pack measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 g (25 g with connecting cable). The packs were secured using double-sided mounting tape. One triaxial accelerometer pack was located at the rigid base of the pilot seat for estimating the vibration entering the seating system. Two packs were located on the top and back of the helmet, respectively, for estimating the helmet multi-axis translations and pitch rotation. Acceleration pads were used to mea-

sure the vibration transmitted to the occupant via the seat pan and seat back. Each pad consisted of a flat rubber disk measuring approximately 20 cm in diameter and weighing 355 g (with connecting cable). A triaxial accelerometer pack was embedded in the disk. The pads were either attached to the seat pan and seat back cushions using double-sided adhesive tape or sewn onto the respective cushions. Cable connections between the accelerometers and DAU were made via breakaway connectors that required less than 21.8 N to separate. A triggering device weighing 20 g was used to initiate the data collection during each event. The DAU was set up to automatically collect simultaneous data from all channels for 90 s on pilot initiation. The acceleration data were low-pass filtered at 250 Hz (anti-aliasing) and digitized at 1024 samples per second. The digitized data were downloaded onto a computer at the end of each mission.

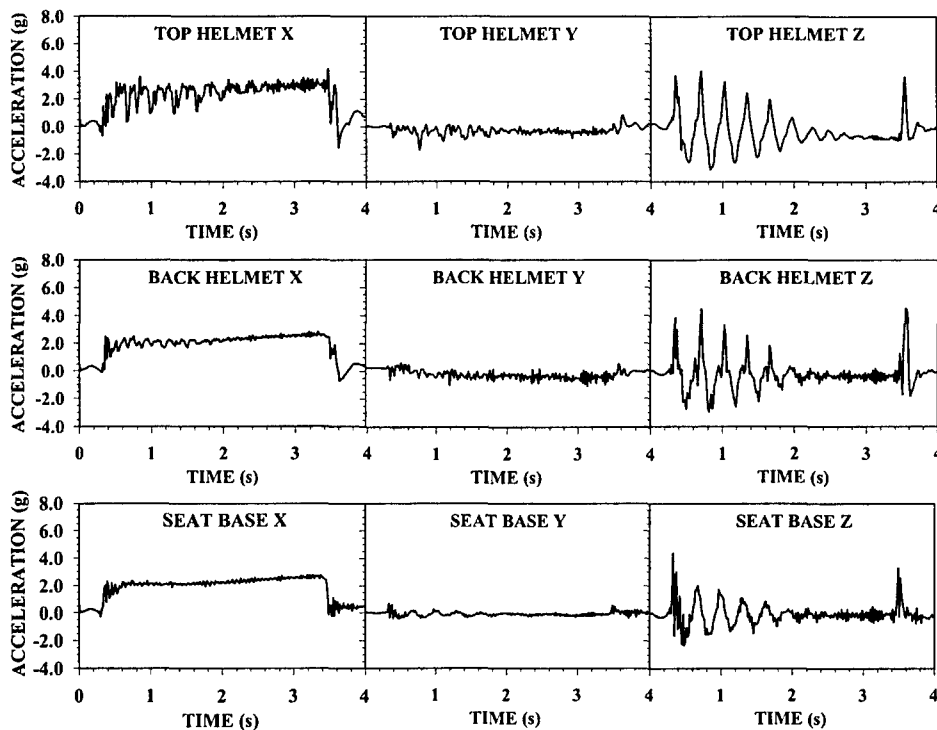
Data were collected from two F/A-18C Hornet aircraft during two mission periods with one pilot (Pilot 1) on Carrier A. The events included six CATs, five TGs, and one TRAP. Data were also collected from one F/A-18C Hornet during three mission periods with two pilots (Pilot 1, Pilot 2) on Carrier B. The events included five CATs, four TGs, and three TRAPs. Pilot 1 participated in data collection on both Carriers A and B. Data from two of the missions on Carrier B were obtained from the same pilot (Pilot 2). Both test pilots were from Test and Evaluation Squadron 23, Patuxent River Naval Air Station, MD. The pilots wore standard flight helmets without helmet-mounted devices.

Profiles of 10 s each were extracted from the measured 90-s segments to include the clearly observed event (CAT, TG, TRAP). For the two mission periods on Carrier A, data processing and analysis were limited to the triaxial accelerations measured at the helmet top and seat base, and the Y and Z accelerations measured at the seat pan. From the 10-s profiles collected on Carrier B, helmet pitch acceleration was estimated as the difference between the acceleration measured in the Z direction at the helmet top and helmet back divided by the length of the moment arm between the two helmet measurement sites, estimated from photographs. Helmet pitch displacement was estimated from the helmet pitch acceleration. Since the pitch profiles did not end at the same point, the mirror image of the signature was appended to the end of the original profile to minimize possible end effects. The resultant profile could then be treated as one cycle of a periodic signal. The Fast Fourier Transform (FFT) of the extended profile was calculated. All complex components occurring at frequencies whose absolute values were 2 or less were set to 0 (mimicking a 2 Hz high-pass filter). In order to obtain the displacement, the complex FFT components were multiplied by $-1 \cdot \omega^{-2}$, where ω is the frequency in radians per second. The inverse FFT was applied to the complex displacement frequency components and the resulting displacement truncated back to the original time interval (9,10).

In order to isolate the vibration to a lower frequency range of concern, each 10-s profile was resampled at 64 samples \cdot s⁻¹, providing data points at 0.016 s intervals



a.



b.

Fig. 1. Representative cockpit seat and pilot helmet triaxial accelerations measured during the CAT: a.) Carrier A, Pilot 1, CATB5 (helmet top and seat base only); b.) Carrier B, Pilot 1, CATA3.

(Matlab®, The Mathworks, Inc., Natick, MA). The process applies an anti-aliasing FIR filter with a Kaiser window. Each specific event (CAT, TG, TRAP) was further isolated from the resampled data by extracting a 4-s time history segment from each 10-s profile. Welch's Method (9,10) was applied to the 4-s time histories to estimate the acceleration and displacement power-spectral densities. This method further divided the signals into 2-s segments with 50% overlap (3 segments). A Hamming window was applied to these segments, and the resultant power spectral densities averaged. The rms acceleration levels were calculated as

$$RMS_i = \sqrt{(PSD_i * 0.5)} \quad \text{Eq. 1}$$

where i represents the i th frequency component and 0.5 is the frequency resolution. The frequency bandwidth was 32 Hz (Nyquist frequency). The results were used to confirm major frequency components associated with each event. All acceleration and displacement results reported in this study are with respect to the resampled data.

RESULTS

In general, the seat base, seat pan, and seat back showed similar acceleration levels for each event, with some exceptions as described below. **Fig. 1** illustrates the actual seat and helmet translational accelerations

measured during a CAT on board both Carrier A (Fig. 1a) and Carrier B (Fig. 1b). These time histories are characteristic of the data collected for the 11 CATs. The initial shuttle release was marked by a sudden increase in the seat X acceleration to approximately 3 g on Carrier A and approximately 2 g on Carrier B. In the seat Z direction, higher frequency oscillations (around 20 Hz or greater) were initially observed with the maximum level ranging between 4–5 g (with resampled data), followed by an abrupt deceleration with a maximum level of about –2 to –3 g. From the time histories, it appeared that the catapult stroke lasted between 2.0–2.5 s on Carrier A (Fig. 1a). The catapult stroke period tended to be longer on Carrier B, lasting between 2.5–3 s (Fig. 1b). The difference was most likely due to the longer catapult stroke length on Carrier B. In addition, there appeared to be a gradual increase in the X acceleration during the stroke period that was more pronounced on Carrier B, where the highest increases reached 1–1.5 g. This increase is not shown in the example depicted in Fig. 1b. In the Z direction, very distinct low frequency vibration was observed following the catapult release that gradually dampened out prior to the end of the stroke period (Figs. 1a and 1b). The highest seat Z accelerations approached 6 g peak-to-peak at the seat pan, with the seat pan tending to show higher accelerations as compared with the seat base. At the end of the stroke, the seat accelerations returned to the original level in the X direction. In the Z direction, the seat accelerations suddenly increased and then rapidly decreased, with the higher frequency oscillations reaching peak-to-peak levels between 5–9 g and the higher accelerations tending to occur at the seat pan.

Low frequency oscillations were observed at the helmet in the X direction during the first 1–1.5 s of the stroke period. These motions were more substantial as compared with the small oscillations observed, to varying degrees, at the seat, as shown in Fig. 1. While the X oscillations are clearly seen at the top of the helmet for both pilots in Fig. 1, these oscillations were even more dramatic for Pilot 2 at both the helmet top and back measurement sites (not shown). The highest helmet X accelerations reached about 6 g peak-to-peak (Pilot 2). As observed at the seat, the helmet also showed very distinct low frequency Z vibration, following the catapult release, that gradually dampened out prior to the end of the stroke. The highest helmet Z accelerations reached almost 8 g peak-to-peak. The coincidence of the low frequency X and Z motions at the helmet during the stroke period suggested the presence of helmet pitch. Differences in the vibration measured at the top and back of the helmet in a specific direction also indicated the presence of helmet pitch. The helmet X peak-to-peak motions associated with the end of the stroke appeared to be higher than the peak-to-peak motions observed at the seat, as dramatically shown in Fig. 1a at the top of the helmet. However, the higher frequency Z seat vibration (noise) observed at the beginning and end of the stroke period appeared dampened at the helmet.

Fig. 2 illustrates the estimated Z rms acceleration

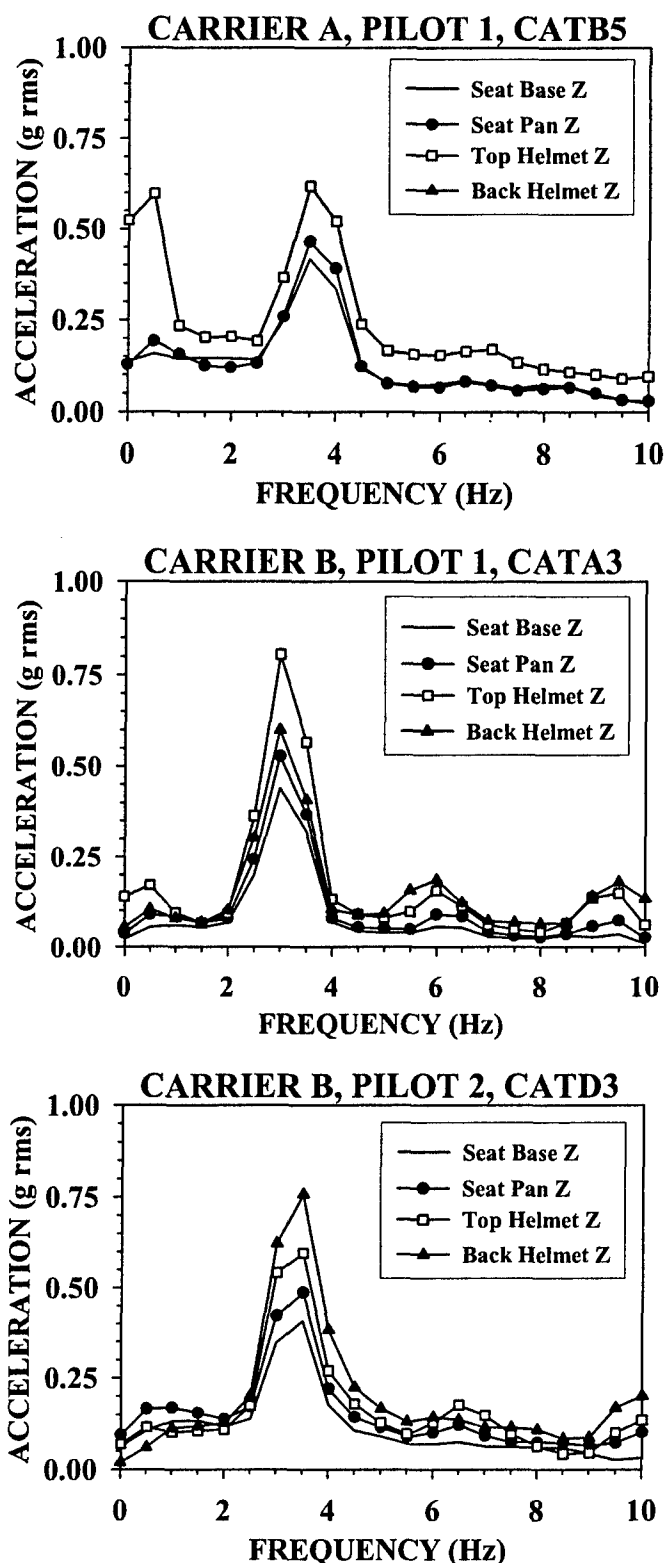


Fig. 2. Examples of the estimated Z rms acceleration frequency responses for the CAT.

frequency spectra at the seat and helmet for three of the CATs. The spectral data confirmed the presence of relatively high magnitude low frequency vibration at around 3–3.5 Hz and the relative differences in the peak magnitudes occurring between the seat base, seat pan, and helmet. Differences were also observed in the ver-

tical motions at the top and back of the helmet between the two pilots (Carrier B). The relatively high Z helmet motion observed at 0.5 Hz for Pilot 1 during the CATs on Carrier A (Fig. 2) most likely reflected the decrease in the helmet sustained acceleration observed during the stroke period. The deceleration reached -2 g at the end of the stroke period as illustrated in the example shown in Fig. 1a. The deceleration was not observed at the seat. As indicated in Fig. 1, Y vibration at the helmet was relatively low compared with the other directions. However, higher levels of Y oscillations tended to occur at the helmet as compared with the seat.

Fig. 3 illustrates the actual seat and helmet translational accelerations measured during a TG (Carrier B, Pilot 2, TGD6) and are characteristic of the data collected for the nine TGs. Low frequency vibration associated with the TG was, in general, of lower acceleration magnitude as compared with the CAT, particularly in the vertical direction, and occurred primarily below 10 Hz as confirmed in the acceleration frequency spectra (not shown). Seat oscillations associated with the initial contact between the aircraft and carrier deck were observed in all three directions as shown in Fig. 3a. While the higher frequency vibration observed at the seat tended to be dampened at the helmet, lower frequency helmet motions were observed in both the X and Z directions. The maximum peak-to-peak helmet motions approached 4 g in the X direction (top helmet, Carrier A, Pilot 1, TGA10), and 5 g in the vertical direction (back helmet, Carrier B, Pilot 2, TGB10). The helmet motions were noted in both directions for Pilot 2 and primarily in the X direction for Pilot 1, and were limited to a few cycles. Fig. 3a shows that very low frequency motion (about 2 Hz or less) occurred in the Z direction at both the seat and helmet, but was completely dampened after about 2–3 cycles.

Fig. 3b illustrates the actual seat and helmet translational accelerations measured during a TRAP (Carrier B, Pilot 1, TRAPA5) and are characteristic of the data collected for the four TRAPs. The most marked feature associated with the TRAP was the increase in the X deceleration occurring within the first second of the event. The deceleration was constant for a 1–2 s period followed by an increase in the acceleration. Again, higher frequency vibration was dampened at the helmet. Low frequency X oscillations (less than 10 Hz) were noted at the helmet, particularly during the initial deceleration period. Very low accelerations were observed in the Y direction. The initially high helmet accelerations reached maximum oscillations of around 5 g in both the X (top helmet, Carrier B, Pilot 2, TRAPD7) and Z (back helmet, Carrier B, Pilot 2, TRAPD7) directions. As with TG, very low frequency oscillations (approximately 2 Hz or less) were observed, but lasted for a longer period of time during the TRAP.

Fig. 4 illustrates representative helmet pitch accelerations and displacements estimated from the translational data collected on board Carrier B for the CAT, TG, and TRAP. Table I lists the maximum helmet pitch peak-to-peak displacements associated with the initial catapult stroke period, end of stroke, initial deck contact during the TG, and initial deck contact during the

TRAP for all measured events on Carrier B. Differences in the peak-to-peak helmet pitch displacements were observed between the two pilots during each specific event, as well as for an individual pilot during a repeated event. As suggested by the translational data shown in Figs. 1 and 3, the highest helmet pitch accelerations and displacements occurred during the CAT. The helmet pitch displacements were particularly dramatic during the initial stroke period, ranging from approximately 9° peak-to-peak to 17° peak-to-peak (Table I), with substantial motions occurring around 3–3.5 Hz as confirmed by the acceleration frequency spectra (not shown). Both the helmet pitch accelerations and displacements coincided with the seat and helmet translational motions observed during the initial stroke period in the X and Z directions (Fig. 1). The pitch motions were dampened prior to the end of the stroke period. At the end of the stroke, the pitch displacements increased again (Fig. 4), ranging from 9° peak-to-peak to 18° peak-to-peak at low frequency. Although the seat pan responses were similar, variable peak-to-peak helmet pitch was observed during the five launches on board Carrier B. As shown in Table I, Pilot 1 showed the highest helmet pitch during the initial stroke period (A2), while Pilot 2 showed the highest helmet pitch at the end of the stroke period (B3).

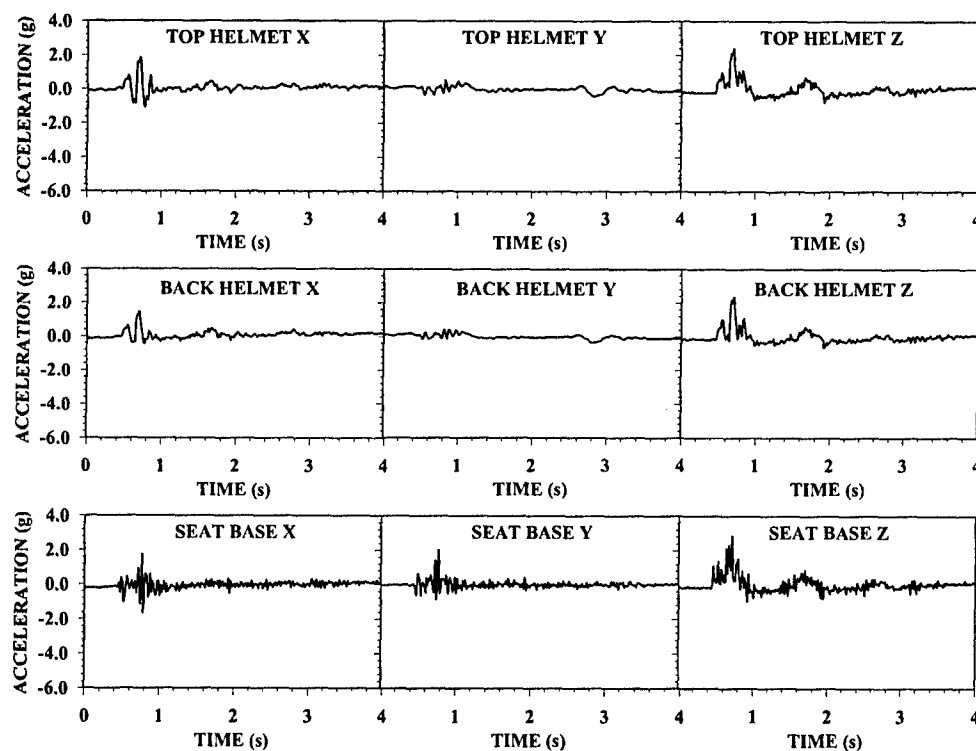
As depicted in Fig. 4 and Table I, the helmet pitch motions associated with TG were relatively small. The peak helmet pitch accelerations coincided with the translational responses occurring during initial deck contact (Fig. 3a) and were limited to a few cycles. The low frequency helmet pitch displacements occurring around 2–3 Hz were confirmed by the acceleration frequency spectra (not shown).

During the TRAP, the highest helmet pitch motions occurred within the first second of the activity (Fig. 4), as suggested by the presence of both X and Z helmet oscillations in the translational data (Fig. 3b) on initial contact with the deck. These pitch motions were higher as compared with the initial motions observed during the TG, as documented in Table I for the peak-to-peak displacements. The concentration of vibration at low frequencies below 10 Hz was confirmed by the acceleration frequency spectra (not shown).

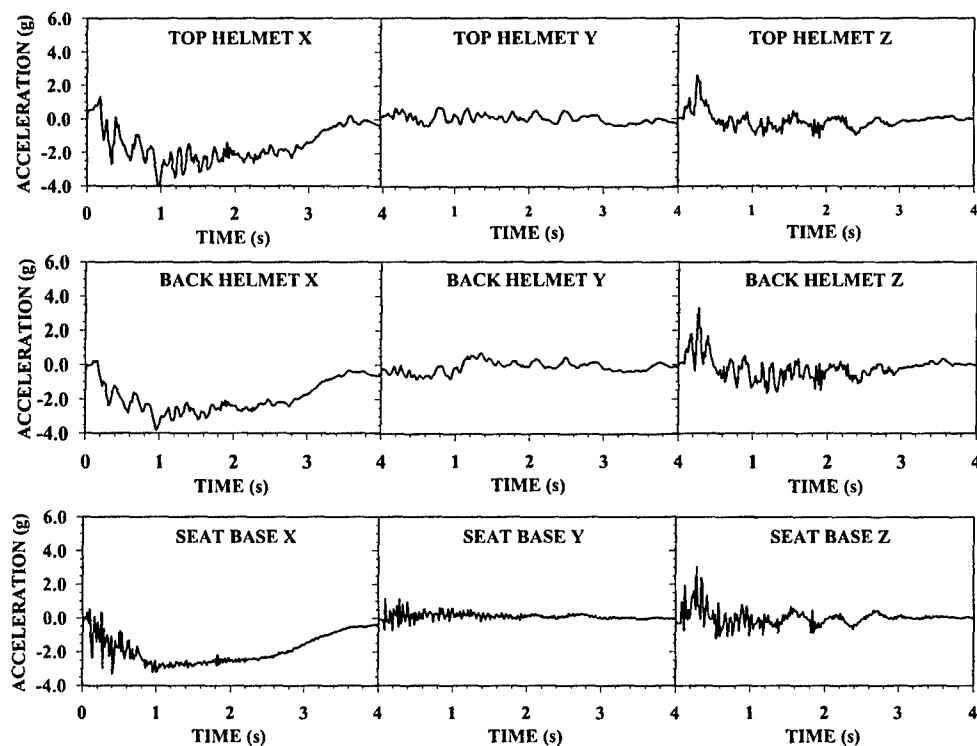
DISCUSSION

This study measured and characterized the vibration occurring at the cockpit seat and pilot helmet in the F/A-18C aircraft during the CAT, TG, and TRAP on board two aircraft carriers. The most marked feature among all of these events was the low frequency vibration (3.5 Hz and below) measured at the seat and helmet during the CAT, particularly in the vertical translational measurements and in the helmet pitch estimations. These low frequency oscillations were most likely due to the reaction of the landing gear strut mechanism. On release of the catapult shuttle, the strut mechanism was initially excited, but the motion dampened as the aircraft traveled down the deck. The brief oscillations occurring at the end of the stroke also appeared to be associated with the reaction of the struts when the catapult shuttle hit the water break. Following

SEAT AND HELMET VIBRATION—SMITH



a.



b.

Fig. 3. Representative cockpit seat and pilot helmet triaxial accelerations measured during a. TG (Carrier B, Pilot 2, TGD6) and b. TRAP (Carrier B, Pilot 1, TRAPA5).

the end of the stroke, the aircraft remained on the deck for about another quarter of a second. During the TG, the results suggested that the initial low frequency motions observed at the seat and helmet were due to the reaction of the landing gear struts on initial contact with the carrier deck, as the motion disappeared once the

aircraft was airborne. In the case of the TRAP, the aircraft remained in permanent contact with the deck and the low frequency motions eventually dampened out. With the limitations imposed on measuring operational vibration, and the suggestion that the helmet motions may vary among individuals, higher (or lower)

SEAT AND HELMET VIBRATION—SMITH

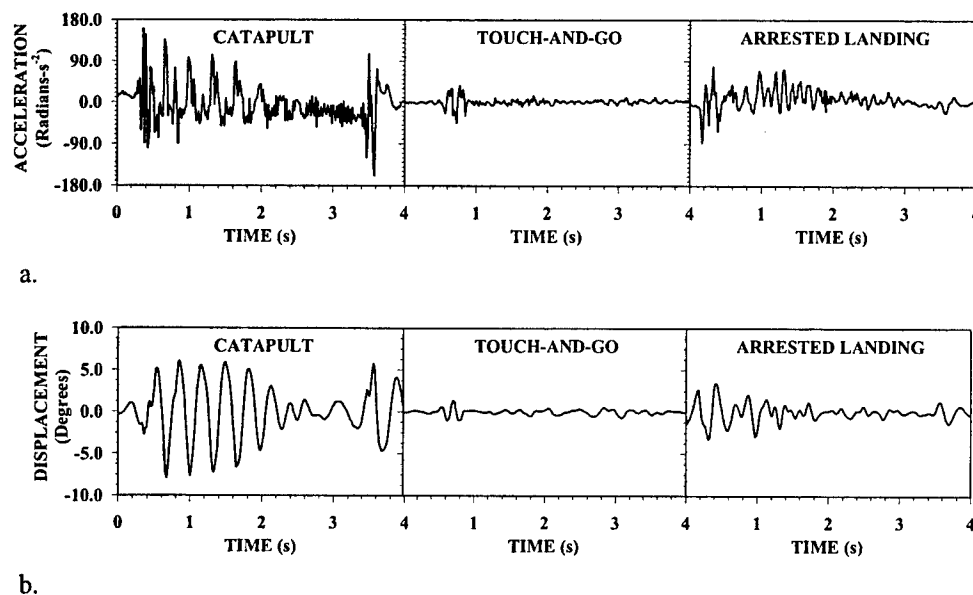


Fig. 4. Representations of a. helmet pitch accelerations, and b. helmet pitch displacements estimated during the CAT (Carrier B, Pilot 1, CATA3), TG (Carrier B, Pilot 2, TGD6), and TRAP (Carrier B, Pilot 1, TRAPA5).

levels of low frequency vibration (below 10 Hz) may occur for all three events investigated in this study among a larger population of pilots and aircraft.

The oscillations or vibration measured in this study did not appear to be of any immediate consequence to the pilots' health. Both test pilots were experienced with carrier flight operations and have not reported any health symptoms related to this activity. The results of this study do suggest that there may be potential consequences of carrier flight operations on the performance of helmet-mounted equipment, particularly when considering the use of the helmet-mounted display as the primary flight reference. During the CAT in particular, the helmet rotational motions were quite high. These rotations could compromise the effectiveness of compensatory eye movement in stabilizing the projected image. The rotational motions are of greater concern than the translational motions when using an HMD since the image is typically collimated and at optical infinity. However, the low frequency motions disappear once the aircraft leaves the deck. If the HMD is not critical during the CAT, then any visual blurring during the catapult stroke period may be inconsequential.

It was not known to what extent helmet slippage contributed to the rotational motions measured during the operational vibration exposures. A method for calculating helmet slippage was developed in this laboratory (11) but would not have been suitable for use

during carrier deck flight operations. The focus of the previous study was on the effects of head/helmet orientation on head/helmet motion, helmet slippage, and tracking performance more associated with the use of helmet-mounted targeting and display systems and did not address these effects on the HMD. The multi-axis flat acceleration spectrum used in the study did show a maximum displacement spectrum of around 2.5 Hz, as expected given the relationship between displacement and acceleration. The peak head, helmet, and helmet slippage pitch displacements were observed in the frequency range of 2–6 Hz. While the peak head pitch transmissibility during exposure to vertical vibration has been reported to occur primarily above 4 Hz (most noticeably between 5 and 6 Hz) (7), vibration exposure at lower frequencies can cause significant head/helmet displacements and possible helmet slippage as suggested in the previous study (11). It is noted that the helmet displacements measured during carrier flight operations were substantially higher as compared with the displacements measured in the laboratory study. The question that remains is what amount of slippage would be required to cause partial or complete loss of a projected image. This slippage depends on the frequency and amplitude of the motion as well as the helmet fit and warrants further investigation. Any image vignetting is undesirable for a primary flight reference and could lead to serious performance degradation once the pilot leaves the deck.

TABLE I. MAXIMUM PEAK-TO-PEAK HELMET PITCH DISPLACEMENTS (DEGREES) (CARRIER B).

Catapult Launch			Touch-and-Go		Arrested Landing	
ID	Begin	End	ID	Contact	ID	Contact
Pilot 1 (CATA2)	17.26	9.31	Pilot 2 (TGB10)	2.16	Pilot 1 (TRAPA5)	6.82
Pilot 1 (CATA3)	13.99	10.43	Pilot 2 (TGD4)	1.94	Pilot 2 (TRAPB7)	3.27
Pilot 2 (CATB3)	9.26	18.34	Pilot 2 (TGD5)	2.19	Pilot 2 (TRAPD7)	4.26
Pilot 2 (CATB6)	12.05	9.15	Pilot 2 (TGD6)	2.4		
Pilot 2 (CATD3)	13.10	10.91				
MEAN	13.13	11.63	MEAN	2.17	MEAN	4.78
SD	± 2.91	± 3.82	SD	± 0.19	SD	± 1.83

In addition to helmet fit, other factors that may have influenced the helmet motion included voluntary head motion by the pilot, pilot posture, neck musculature, and sitting height. These factors could be partly responsible for the differences observed between pilots as well as differences observed for the same pilot between similar events, particularly when the input motions at the seat were similar. In the controlled laboratory environment of the previous study (11), variability was observed in the head/helmet and helmet slippage pitch displacements among the subjects. The previous study also showed some effect of helmet weight distribution on the helmet pitch and helmet pitch slippage displacements (11) that could be an issue in the design of an HMD for use during carrier flight operations.

One of the primary goals of this study was to document human vibration during F/A-18C carrier flight operations. These data provide the signatures for regenerating the operational exposures in the laboratory. The great advantage is the opportunity to investigate many of the issues described above in the controlled laboratory environment. Helmet slippage, HMD image vignetting, and visual blurring caused by ineffective compensatory eye movement during exposure to the carrier flight events could be estimated. Likewise, the laboratory environment provides the platform for designing and testing appropriate mitigation strategies for optimizing the performance of helmet-mounted equipment and insuring the safety of aircrews in operational vibration environments.

ACKNOWLEDGMENTS

This study was conducted on board the *USS John F. Kennedy* (CV 67) and the *USS Abraham Lincoln* (CVN 72). The author would like to acknowledge the Joint Strike Fighter Program, Air Vehicle Systems Engineering & Integration, Environment Integrated Product Team, specifically Mr. James D'Andrade from the Naval Air Warfare Center, and Mr. Richard McKinley from the Air Force Research Laboratory, for organizing and supporting this study. A very special thanks goes to Test and Evaluation Squadron 23, Patuxent River Naval Air Station, MD, for their participation and guidance on this unique project. Their support is greatly appreciated. The author also expresses gratitude to the carrier suitability personnel who assisted with the instal-

lation of the equipment. Finally, the author acknowledges the assistance of Mr. Raymond Newman of Veridian Engineering and Capt. Charles Loyer, USAF.

REFERENCES

1. Alem NM, Meyer MD, Albano JP. Effects of head supported devices on pilot performance during simulated helicopter rides. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory; 1995. Report No: USAARL-95-37.
2. Barazanji KW, Alem NM. Effects of head-supported devices on female aviators during simulated helicopter rides. Part 1. Biomechanical response. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory; 2000 June. Report No: USAARL-2000-16.
3. Benson AJ, Barnes GR. Vision during angular oscillation: The dynamic interaction of visual and vestibular mechanisms. *Aviat Space Environ Med* 1978 (Section II); 49:340-5.
4. Butler BP. Helmeted head and neck dynamics under whole-body vibration [Dissertation]. Ann Arbor, MI: University of Michigan; 1992.
5. Furness TA, Lewis CH. Helmet-mounted display reading performance under whole-body vibration. Proceedings of the United Kingdom Informal Group on Human Response to Vibration; 1978 Sept 18-20; Silsoe, UK: National Institute of Agricultural Engineering; 1978.
6. International Organization for Standardization. Mechanical vibration and shock - mechanical transmissibility of the human body in the z direction. Geneva: ISO; 1987; ISO 7962 1987.
7. Paddan GS, Griffin MJ. The transmission of translational seat vibration to the head. 1. Vertical seat vibration. *J Biomechanics* 1988; 21:191-7.
8. Smith SD. The effects of head orientation on head/helmet vibration response. *SAFE Journal* 2000; 30:114-25.
9. Smith SD, Smith JA, Newman RJ. Helmet system performance in vibration environments. Proceedings of the United Kingdom Group on Human Response to Vibration; 2000 Sep 22-24; Dunton, UK: Ford Motor Company; 2000.
10. Smith SD. Collection and characterization of pilot and cockpit buffet vibration in the F-15 Aircraft. *SAFE Journal* 2002; 30: 208-18.
11. Smith SD, Smith JA, Newman RJ. Head motion and helmet slippage during exposure to whole-body vibration. Proceedings of the North Atlantic Treaty Organization (NATO) Research and Technology Organization (RTO) Specialists' Meetings on Equipment for Personal Protection (AVT-097/RSM-012) and Personal Protection: Biomechanical Issues and Associated Physio-Pathological Risks (HFM-102/RSM-006); 2003 May 18-23; Koblenz, Germany (In press).
12. Stott JRR. The vertical vestibulo-ocular reflex and ocular resonance. *Vision Res* 1984; 24:949-60.